

AIR POLLUTION IN ROAD TUNNELS

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AIR POLLUTION IN ROAD TUNNELS

BY

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As a part of a study of pollution of the air by motor vehicles, measurements have been made in two London road tunnels during periods of high traffic density. The concentrations of smoke and polycyclic hydrocarbons found there are much higher than the average values in Central London, but they are of the same order of magnitude as those occurring during temperature inversions on winter evenings when smoke from coal fires accumulates at a low level.

An attempt has been made to relate the concentration of each pollutant to the type and amount of traffic. Both diesel and petrol vehicles make some contribution to the amounts of smoke and polycyclic hydrocarbons found in the tunnels, but in the case of smoke, fluoranthene, 1:2-benzpyrene, pyrene, and 3:4-benzpyrene, the concentrations appear to be more closely related to the density of diesel traffic than to that of petrol traffic. The concentrations of lead and carbon monoxide have also been determined, and these are very closely related to the density of petrol traffic. During the morning and evening rush hours the mean concentration of carbon monoxide was just over 100 p.p.m. and peak values up to 500 p.p.m. were recorded at times. Oxides of nitrogen were determined in some of the experiments and there was always much more nitric oxide than nitrogen dioxide. Eye irritation was experienced but its cause was not investigated.

The concentration of pollution in the tunnels does not appear to be high enough to create any special hazards for short-term exposures. The atmosphere at peak periods may become very dirty and unpleasant and the concentration of carbon monoxide would be sufficient to produce some effect over a period of several hours' continuous exposure. The total emission of pollution from road vehicles must still be small in comparison with that from coal fires, but the effect of traffic on the concentration of smoke, polycyclic hydrocarbons, carbon monoxide, and lead in the air of city streets deserves continued study.

Although the combustion of coal is still responsible for most of the air pollution in British towns, the contribution made by motor vehicles deserves careful attention. In an earlier paper (Commings, Waller, and Lawther, 1957) the concentrations of smoke and polycyclic hydrocarbons in two London diesel bus garages were compared with those in the outside air. In each case there was much more black smoke inside the garage than outside, but the differences in 3:4-benzpyrene concentration were small. The buses were in excellent mechanical condition and they were being run under minimal load. The results of this investigation were relevant to the health of the workers in the garages, but they were of strictly limited value in any study of the possible effects on the general population of pollution from vehicles.

The highest concentrations of pollution from motor vehicles occur in tunnels, and to study the

emissions from mixed traffic, measurements were made in two London road tunnels under the Thames. Our earlier experiments had shown that the smoke from buses contains much lower proportions of polycyclic hydrocarbons than domestic coal smoke, and to avoid any interference from the latter the experiments were confined to warm days during the summer months.

Sampling Sites

The Blackwall and Rotherhithe tunnels carry all types of traffic, including regular bus services, private coaches, lorries, cars, and motor cycles. They are open also to pedestrians and cyclists, but are little used by them. Cleaning and maintenance staff spend limited periods in the tunnels and any major work is done when there is little traffic. There is no routine traffic control in either tunnel.

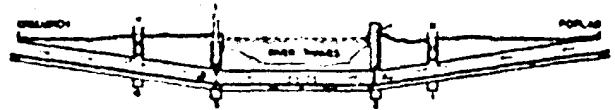


Fig. 1.—Section through Blackwell Tunnel, showing ventilation system.

At the time of these studies the Blackwell Tunnel was normally busier than the Rotherhams and, because higher pollution was expected, most of our measurements were made there. There are corners and gradients to be negotiated in each tunnel and driving conditions are similar to those in highly congested streets. The composition of the traffic varies with the day of the week and with the time of day, and we took advantage of this fact to try to assess the separate contributions of petrol and diesel traffic to the pollution of the tunnel atmosphere. At all times there are fewer diesel than petrol vehicles, the proportion varying between about 2% on Sunday evening to over 30% at noon on weekdays.

The Blackwell Tunnel (Fig. 1) is 1,490 yards long and it connects the busy dock area around Poplar with Greenwich and the roads to the Kent coast. When opened in 1927 it was ventilated by four shafts, each 46 ft. in diameter, but fans had to be installed in them at intervals between 1922 and 1940 as the volume of motor traffic increased. The fans can be operated separately, but usually all are in use throughout the day, some are switched off in the evening, and all are off at night. The main requirement is to keep the concentration of carbon monoxide within reasonable limits, but this is sometimes difficult during prolonged hold-ups and drivers are warned to switch off their engines in these conditions. Smoke haze is usually visible in the tunnel and the atmosphere is often irritant to the eyes. Fresh air is ducted to the centre of the tunnel and also enters at the ends. The extractor fans in shafts 1 and 4 draw air from each direction, but in practice the section between the centre of the tunnel and shaft 4 is poorly ventilated. The maximum emission of pollution occurs near the bends at the foot of each shaft, where large vehicles often have to halt and then pull away up the inclines. Strong winds blowing into the ends of the tunnel can alter the pattern of ventilation, but pollution appeared to be highest between shafts 3 and 4 or between 1 and 2. The sampling points were sited in one of the sections having high smoke pollution, their exact position being dictated by considerations of safety and accessibility. In the first series of experiments (1958) the

samplers were placed on a shelf 7 ft. above pavement level at a point A (Fig. 1), and in the second series (1959) they were placed on a similar shelf at point B.

The Rotherhams Tunnel is 1,430 yards long and it connects Stepney and Bermondsey. It was opened in 1904 and fans were installed between 1924 and 1932. The general layout is similar to that of the Blackwell Tunnel, but the bends do not seriously interfere with the flow of traffic. During the period of this study the Blackwell Tunnel was closed throughout some week-ends whilst alterations were being made to the approach road, and the Rotherhams Tunnel then carried much extra traffic. On one of these occasions samples were taken there at a point between two of the shafts, where pollution was high, using a shelf mounted 7 ft. above pavement level as in the Blackwell Tunnel.

The pollution problems encountered in these tunnels during the period 1928 to 1931 when the ventilation systems were being redesigned have been discussed by Regan (1932).

Traffic Counts

Throughout each of the experiments the flow of traffic was determined by observers standing inside or just outside the tunnel. The counts were divided into consecutive 10-minute periods, figures for each direction being recorded separately, but for most purposes the results were later expressed as vehicles per hour in either direction. Initially the vehicles were classified as "private" or "commercial" to give some indication of the proportion of petrol and diesel vehicles. Virtually all private vehicles have petrol engines and more detailed counts showed that approximately 50% of the commercial vehicles using the tunnel had diesel engines. After studying the types of vehicles in common use and drawing up a list of features to aid rapid recognition of diesel vehicles it became possible to count "petrol" or "diesel" directly and all the figures in Tables 1 to 4 have been expressed in this form.

Experience soon showed that the flow of traffic did not provide an adequate index of the emission of pollution in the tunnel. This is likely to vary with the number of vehicles in the tunnel at a given instant

and there may be a high traffic density even if the flow in vehicles per hour is low or nil. The most relevant parameter appeared to be the number of vehicles within the ventilation section in which we were working. In some experiments this was measured directly by observers stationed at each end of the section, who were in contact by telephone. When an easily recognizable vehicle passed one observer, he sent a message to the second observer who then counted and classified all vehicles passing him until the "marker" vehicle reached him. To avoid possible bias due to the selection of diesel vehicles as markers this technique was abandoned for purposes of defining the composition of the traffic. In general, it was simpler to time vehicles over the section. When necessary this was done by the two observers connected by telephone but often it was possible for one observer to walk alongside the vehicles or to stand half-way watching vehicles entering and leaving the section. The timings were made frequently and each direction was recorded separately in the first instance. From these figures mean times were calculated for each sampling period. The ventilation section considered here was that between shafts 1 and 2 (146 yards) when sampling at point A and between shafts 3 and 4 (201 yards) when at B. An estimate of the traffic density during each period was then obtained by multiplying the flow in vehicles per hour by the mean time in fractions of an hour taken to traverse the section. Results of the later experiments showed that this provided a useful statistic, although it did not take into account any variations in the emission of pollution with running conditions. The speeds of the vehicles were calculated from the times and the mean figures are quoted in Tables 1 to 4.

Procedure

During the summer of 1958 four visits were made to the Blackwall Tunnel and one to the Rotherhithe Tunnel. Congestion appeared to be greatest during the morning rush hour and samples were taken at this time on July 3 and August 20. An evening rush hour (August 1) was also studied, for there was at that time a greater proportion of petrol-engined traffic. The proportion may have been higher than on an average evening since it was the Friday before a Bank Holiday week-end. In an attempt to study almost "pure" petrol traffic further samples were taken during the late evening on Bank Holiday, August 4, when thousands of cars were returning from the coast. The traffic was fairly fast on this occasion, for it was mainly in one direction and there were few large vehicles to cause obstruction at the bends. There were some diesel buses and coaches but few lorries. All the samples up to this time were collected

at point A (Fig. 1). A similar sample was taken in the Rotherhithe Tunnel on September 14 when the Blackwall Tunnel was closed and there were again thousands of cars returning from the coast on a warm Sunday evening.

An analysis of the results of these preliminary experiments showed that there was a general relationship between the concentration of each pollutant and the density of traffic, but the large number of variable factors precluded any attempt to discriminate between the effects of petrol and diesel traffic. Big differences in the type or amount of traffic were attended by big differences in speed, and variations in wind speed and direction from one day to another were sufficient to cause differences in ventilation rate at our sampling point.

Further experiments were deferred until the summer of 1959, but in the meantime additional traffic counts were made and the pattern of pollution along the tunnel was checked visually on a number of occasions. High pollution was encountered more often at the southern end of the tunnel than at the northern, and the sampling shaft was moved to point B (Fig. 1).

To minimize the effects of variations in ventilation rate a series of experiments was planned for a single day when there was a steady wind. It was found that on a normal week-day the number of diesel vehicles using the tunnel reached a maximum towards midday and the number of petrol vehicles was highest around 6 p.m. Arrangements were therefore made to sample continuously from 10 a.m. until 7 p.m. so as to include these two peaks. To avoid interference from domestic smoke the experiment was scheduled for a very warm day when few fires would be in use. The weather became fine and warm in early May and the experiment was carried out on Thursday May 6 when the outside temperature reached 70 F. and the wind remained steady at about 3 m.p.h. from a north-easterly direction. An intensive study of pollution was made on this occasion and a team of four observers timed and counted traffic continuously. There would have been some advantage in continuing for a complete 24-hour period, but the experiments proved to be very arduous under the conditions in the tunnel, and with the staff available it was not practicable to continue any longer.

A final experiment was planned to cover an overnight period which we had not previously studied. This was started during the evening of Sunday July 5, one of the hottest days of the year, and lasted until 10 a.m. on Monday. We were thus able to examine the pollution caused by a period of very heavy traffic, consisting mainly of private cars returning from the coast, followed by a quiet period during

TABLE I
RESULTS OF TUNNEL EXPERIMENTS, BUCKNER PASS

[illegible]

*Values per hour in both directions

*Percent of number of children in selected vaccination series for each

the night after which there was the morning rush hour. The flow of cars continued well into the night, but our hopes of sampling "pure" petrol engine pollution at that time were spoiled by the presence of a number of diesel-engined coaches. The wind remained steady at about 9 m.p.h. from a northerly direction during the course of the experiment, but there were some big changes in ventilation when the fans were switched off during the night.

In each of these experiments samples of smoke were taken, usually over periods of one hour, for the determination of polycyclic hydrocarbons, and in the later series (1979) part of each sample was used for the determination of lead. A continuous record of the carbon monoxide concentration was obtained on two occasions (September 18, 1958 and May 14, 1979) and "spot" measurements were made at other times. Oxides of nitrogen were also measured during some of the experiments, but no observations were made on sulphur dioxide. Since the tunnel air enters from four widely separated points it was considered impracticable to define completely the background level of pollution. All the measurements were made at times of very low background pollution and results from observations in Central London were available for comparison.

Sampling and Analytical Methods

The methods used were similar to those employed in the earlier experiments at San Giorgio (Cossens *et al.*, 1977). Samples of silt were collected on weighed glass fibre filter sheets measuring 11 by 10 in. overall, using a Staphis flow volume sampler. Each filter, after weighing, was extracted with cyclohexane for three hours in a Soxhlet apparatus and the yellow extract was reduced to small volume and transferred to a column of alumina. The hydrocarbons were separated chromatographically by elution with cyclohexane and determined spectrophotometrically (Cossens, 1979).

Where lead was determined, the alloy was divided and a measured fraction of it extracted with nitric acid; an aliquot of this solution was extracted with a small excess of dichlorine to chloroform and the excess dichlorine removed by evoking with antimony-potassium cyanide solution (Harrell, Black, and Holden, 1934). The amount of lead in the extract was estimated colorimetrically by a comparison of the red colour of the lead-dichlorine complex.

A recording infra-red analyzer was used to determine carbon monoxide in the tunnel. Spot samples were collected in evacuated bottles and analyzed later in the laboratory.

Chains of nitrogen were collected by passing the island air through nitroed bubblers containing absorbing reagents (Chakman, 1954). Nitrogen dioxide was absorbed

first and the nitric oxide was then oxidized and collected as NO_2 (Thomas, MacLeod, Robbins, Goustimenko, Eldridge, and Rogers, 1954). In the 1979 experiments samples were taken over hourly periods and the colorimetric determinations were made in the tunnel. In some earlier experiments "spot" samples were collected in evacuated bottles and analysed in the laboratory.

Results

The results from each of the experiments carried out during 1954 have been assembled in Table 1. The concentration of "smoke" (including all particulate matter collected by the high volume sampler) ranged from 93 to 235 $\text{mg}/100 \text{ m}^3$. This is many times the concentration in the ordinary London air at that time of year; samples collected by the same method in Central London at intervals throughout the summer gave results ranging from 10 to 25 $\text{mg}/100 \text{ m}^3$. To allow some comparison to be made with our earlier bus garage experiments, results from the mid-summer experiments at Merion have been included in this Table. The figures quoted here refer to the period between 11 p.m. and 1 a.m., when the smoke from the buses was sufficient to raise the concentration in the garage to several times the outside level. Under these conditions there was little error in considering the buses to be responsible for all the pollution in the garage, and direct comparisons can be made with the tunnel results. The concentration of each hydrocarbon is much higher in the tunnel than in the garage, but in view of the difference in ventilation little can be inferred from these figures alone. More useful is the comparison of the composition of the smoke, expressed as micrograms of hydrocarbon per gram of smoke. In this respect also the tunnel results are much higher than those obtained in the garage. This suggests that the petrol and diesel vehicles using the tunnel are producing smoke which is richer in hydrocarbons than that emitted by diesel buses when manoeuvring in garages.

The concentrations of pollutants recorded in this series do not vary consistently with the type or amount of traffic, but the smoke concentration was lowest on the Bank Holiday when there were few diesel vehicles present. The concentrations of most of the hydrocarbons at that time were, however, similar to those obtained on other occasions.

The concentration of carbon monoxide observed during the course of these experiments was generally greater than 100 p.p.m. Most of the samples were collected in evacuated bottles over brief periods, but the result quoted for the Rotherhithe Tunnel is an average value over the one and three-quarter hour period of the main experiment. The infra-red

analyser was left running for two days before and one day after this experiment. The record showed a further increase in concentration after we had left on the Sunday night, reaching a peak of 300 p.p.m. at midnight. High concentrations were also recorded on the Friday evening, with peak values of 450 p.p.m., and again on Saturday evening, with values up to 340 p.p.m.

Several samples were also collected in evacuated bottles for the determination of oxides of nitrogen, but difficulty was experienced in preventing oxidation of nitric oxide before the determinations were made. Concentrations of nitric oxide ranged from 1 to 8 p.p.m., with smaller quantities of nitrogen dioxide. In later experiments continuous samples were taken and the determinations were made in the tunnel.

Detailed results from the hourly samples taken on May 14, 1979 at point B are given in Table 2. The concentration of smoke varied between 149 and 319 $\text{mg}/100 \text{ m}^3$, approximately 10 times that in the air of Central London at that time. The concentrations of smoke and of each of the hydrocarbons were in general higher than those encountered in the earlier experiments at the other end of the tunnel (point A). The concentration of carbon monoxide was measured continuously and peak values of up to 235 p.p.m. were recorded. The results for oxides of nitrogen show a much lower ratio of nitrogen dioxide to nitric oxide than is found in the ordinary atmosphere. The concentration of nitric oxide remained close to 1 p.p.m. throughout these experiments, but there was always less than 0.1 p.p.m. of nitrogen dioxide. There was much more lead in the tunnel than occurs normally in urban atmospheres. The concentrations were of the same order of magnitude as those found by Peub (1957) in a road tunnel in Zurich.

In Fig. 2 the relationship between the concentrations of pollutants and the traffic density is shown graphically. All values have been plotted as percentages of the mean for each series so that hour-to-hour variations can be studied on a common basis. The densities of petrol and diesel traffic follow one another fairly closely during the earlier part of the day but in the evening there is a sharp difference between them. The curves have been grouped so as to separate those which show a pronounced rise during the evening from those which do not. The lead and carbon monoxide graphs (Fig. 2) certainly belong to the former category, and follow very closely that for the density of petrol traffic.

Tetra-ethyl lead is added to most petrol, and fine particles containing lead sulphate, lead bromide, and other compounds are emitted with the exhaust gases (Dotting, 1957); diesel fuel does not contain any

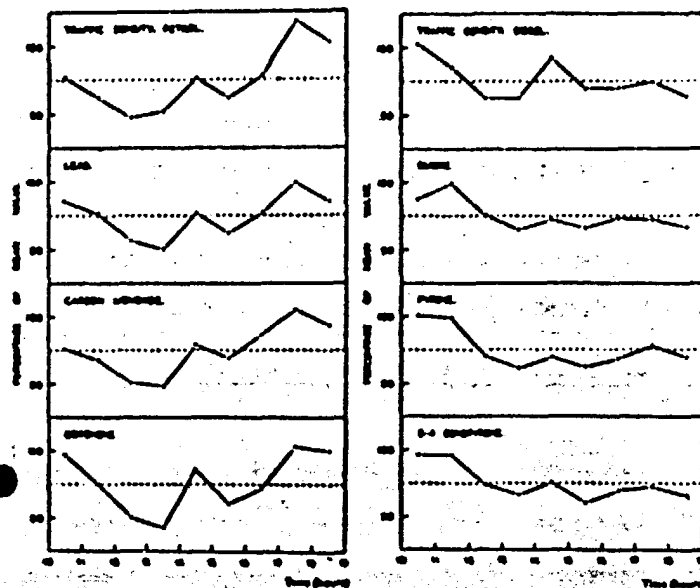


Fig. 1.—Variation in traffic density and concentrations of pollutants in Blackwall Tunnel, May 24, 1968.

appreciable quantity of lead. Petrol engines also produce much more carbon monoxide than diesel engines (Fittion, 1958). We would therefore expect the concentrations of lead and carbon monoxide to vary with the amount of petrol traffic, and the similarity between the curves suggests that the density of petrol traffic is in fact a useful index of pollution from petrol-engined vehicles. The curve for coronene has also been included in this series, for it shows some rise in the early evening; the concentration of 1:12-benzopyrene also varies in a similar fashion.

The concentration of smoke (Fig. 2) does not follow the density of diesel traffic very closely, but the association is certainly closer than with the density of petrol traffic. Since the emission of smoke varies widely with load it may be that the density of the traffic does not provide an adequate index of

pollution in the case of diesel vehicles, but it would be difficult to define the operating conditions in the tunnel sufficiently to produce a better one. Variations in the concentration of pyrene and 3:4-benzopyrene are also shown in Fig. 3 and the concentrations of fluoranthene and 1:2-benzopyrene follow similar patterns. The concentration of anthracene varies rather irregularly.

The quality of the smoke can also be considered from the second part of Table 2. The amounts of most of the hydrocarbons (in μg . per gram of smoke) were similar to those found in the earlier experiments, though it can be seen that there is a tendency for the proportions of coronene and 1:12-benzopyrene in the smoke to increase with the proportion of petrol traffic.

It seems likely from the figures presented so far

TABLE 2
POLLUTION IN BLACKWALL TUNNEL, MAY 14, 1968

	Time (hours)									
	10-	11-	12-	13-	14-	15-	16-	17-	18-	19-20
Trucks, heavy	761	934	1111	1311	1546	1788	1,916	1,364	1,364	1,576
Trucks, light	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 1000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 1500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 2000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 2500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 3000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 3500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 4000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 4500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 5000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 5500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 6000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 6500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 7000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 7500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 8000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 8500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 9000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 9500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 10,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 10,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 11,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 11,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 12,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 12,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 13,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 13,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 14,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 14,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 15,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 15,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 16,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 16,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 17,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 17,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 18,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 18,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 19,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 19,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 20,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 20,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 21,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 21,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 22,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 22,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 23,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 23,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 24,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 24,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 25,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 25,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 26,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 26,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 27,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 27,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 28,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 28,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 29,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 29,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 30,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 30,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 31,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 31,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 32,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 32,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 33,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 33,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 34,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 34,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 35,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 35,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 36,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 36,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 37,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 37,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 38,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 38,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 39,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 39,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 40,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 40,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 41,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 41,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 42,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 42,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 43,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 43,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 44,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 44,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 45,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 45,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 46,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 46,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 47,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 47,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 48,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 48,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 49,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 49,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 50,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 50,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 51,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 51,500 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 52,000 lb.	546	761	1,156	1,311	1,546	1,711	1,916	1,364	1,364	1,576
Trucks, 52,500 lb.	546	761	1,156							

Thousands of numbers of vehicles in different manufacturing series have been

was a temporary increase in pollution soon after 01:00 hours when all the fans were off. Some brief periods of high pollution were also noticed shortly before all the fans were switched on again in the morning.

Broad comparisons can be made between the first three hours of the experiment and the last three. The density of petrol traffic was similar during these two periods, but there was great variation in the density of diesel traffic. The concentrations of smoke and of each of the hydrocarbons were higher when there were more diesel, and this is in accordance with earlier results, but the concentration of lead was also somewhat increased. Since lead is emitted only by petrol engines this unexpected finding may indicate that there were changes in ventilation due to varying winds or that the meteorological flow during the morning period gave rise to a greater emission of lead per unit petrol vehicle than the smoother flow during the evening.

In general the smoke from this series contained smaller amounts of hydrocarbons (expressed as $\mu\text{g per g}$) than that collected in the earlier daytime experiment. This means either that the vehicles were emitting material which was weaker in hydrocarbons than before, or that a greater amount of extraneous dust was being picked up on the second occasion.

TABLE 4
POLLUTION IN BLACKWALL TUNNEL, SUMMARY OF RESULTS

	Blackwall Tunnel					Central London		
	Morning Rush Hour	Evening Rush Hour	Daytime	Holiday Evening	High Minimum	Typical Summer	Typical Winter	Temperature Unusually
Petrol vehicles per hour (Diesel vehicles per hour shown in p. 51)	221 386	1,179 211	271 136	1,074 30	20 11	—	—	—
Smoke (mg. 100 m. ³)	176	360	123	71	23	30	35	270
Lead (mg. 100 m. ³)	21	21	14	14	—	—	—	—
Carbon monoxide (p.p.m.)	736	261	68	136	—	170	170	2600
Hydrocarbons (mg. 100 m. ³)								
Benzene	40	40	100	27	2.0	1.0	2.5	400
1-Benzopyrene	14	14	10	10	0.5	0.5	0.5	10
Toluene	30	30	12	12	0.5	0.5	0.5	10
Cresol	30	30	12	12	0.5	0.5	0.5	10
Anthracene	12	12	10	10	0.5	0.5	0.5	10
1:12-Dibenzopyrene	12	12	10	10	0.5	0.5	0.5	10
1-Benzopyrene	30	30	12	12	0.5	0.5	0.5	10

*Values of great concentrations reported by Williams (1956).

**Highest value in series of measurements except when in busy streets.

and domestic chimneys also emit carbon monoxide and small quantities of lead but these sources are unlikely to contribute significantly to the concentrations occurring amongst heavy traffic. Brief, Jones, and Yoder (1940) have reported close correlations between the concentrations of these pollutants and the amount of traffic in the streets of a north-eastern United States city. These authors did not distinguish between petrol and diesel traffic, but the latter probably formed only a small percentage of the total. In Central London a substantial proportion of the traffic has diesel engines which can be discounted as emitters of lead and carbon monoxide. Our work in streets, garages, and tunnels leads us to support the suggestion of Williams (1956) that the current use of diesel engines in buses and heavy goods vehicles provides one explanation for the lack of any substantial increase in carbon monoxide concentrations in London streets over a period of 34 years, despite large increases in traffic. The relationship seen in our experiments between the concentration of smoke in the tunnel and the density of diesel traffic also seems reasonable. Williams (1961) has shown that "the smoke concentrations from road traffic on busy roads can be appreciable and, for short periods, can produce intense local pollution". In Table 4 the tunnel results have been summarized and compared with outdoor concentrations of smoke and hydrocarbons. The lowest pollution encountered in the tunnel has been tabulated together with the mean values for other periods; the morning "rush hour" figures refer to samples taken between 07.00 and 10.00 hours on week-days, the evening "rush hour" to samples taken between 16.00 and 20.00 hours, and the daytime figures to those taken between 10.00

and 16.00 hours. The "holiday evening" samples were taken in the Blackwall Tunnel on a Sunday or Bank Holiday. The Central London figures provided for comparison are, with the exception of the carbon monoxide, based on results from a number of samples taken in the open air, away from traffic, at St. Bartholomew's Hospital. Typical summer and winter values are quoted together with the results from a sample taken during a period of high pollution on December 3, 1957; the smoke on this occasion came mainly from domestic chimneys and a low temperature inversion prevented it from dispersing normally.

During the quietest period in the middle of the night the concentrations of most pollutants in the tunnel fell to the same order of magnitude as those in the ordinary London air. At other times, when there is heavy traffic, the concentrations of all pollutants measured in this study are much higher than the typical summer or winter levels in outdoor air. The concentrations during the morning and evening rush hours are similar to one another, despite differences in traffic composition. The maximum concentration of smoke occurs in the daytime, when the number of diesel vehicles is highest. The concentrations of most of the hydrocarbons are also highest then, but benzene and 1:12-benzopyrene, which appear to be associated rather more with petrol vehicles, show their highest concentrations during the rush hours. The concentration of carbon monoxide is highest on holiday evenings, when the number of petrol vehicles is at a maximum. The concentration of smoke and of most hydrocarbons is lower than at any other busy time in the tunnel, although it is still many times the outdoor level.

Further comparisons within Table 4 show that all the concentrations of smoke and hydrocarbons in the tunnel are within the range found in ordinary London air. Those observed during busy periods can be regarded as similar to the concentrations of smoke and hydrocarbons found during temperature inversions on winter evenings in Central London. Carbon monoxide appears to be the only significant hazard; during the rush hours and on busy holiday evenings the concentration was generally over 100 p.p.m., which is the maximum allowed for continuous exposure in industry. Exposure to these concentrations for several hours may have perceptible effects and on several occasions during the course of these experiments the authors and their colleagues experienced headache, fatigue, and general drowsiness after being exposed continuously for periods of three to 14 hours in the tunnel. Drivers are not normally exposed to these concentrations for more than 30 minutes in passing through the tunnel and no one else spends long there during the busy periods. Severe eye irritation was experienced at times, but the cause of this was not investigated. The oxides of nitrogen do not appear to present any special hazard. There is much more nitric oxide than nitrogen dioxide in the tunnel air. The concentration of the latter reached about 0.1 p.p.m. (Table 2), which is well below the 5 p.p.m. permitted in industrial atmospheres. The physiological effects of nitric oxide have not been studied widely, but it can combine with the blood in the same way as carbon monoxide. The effects of oxides of nitrogen have been discussed by Katz, Rennie, and Jager (1959), who made measurements in a railway tunnel where diesel trains were operating. They considered that the concentrations of nitric oxide observed

there (of the order of 20 p.p.m. in instantaneous samples) were not sufficient to form detectable amounts of methemoglobin in blood. There is at present no reason to believe that the concentrations recorded in the tunnel (up to 1.4 p.p.m. in continuous estimations, but higher in some spot samples) would produce any effect on man.

Conditions in the Blackwall Tunnel are expected to improve greatly when the twin tunnel now under construction comes into use. The existing tunnel will then be used for traffic in one direction only.

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